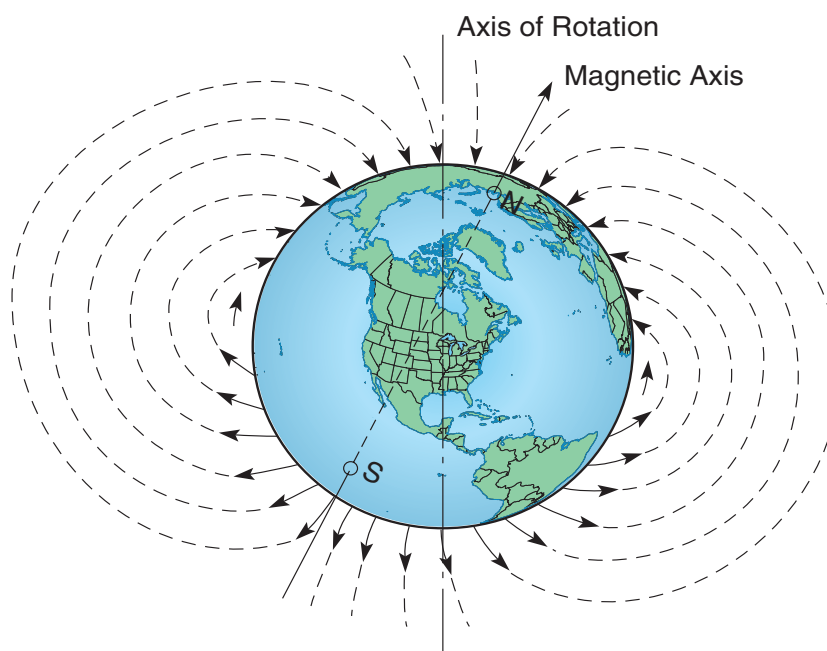


Prepared in cooperation with the U.S. Department of Energy  
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# **Paleomagnetism of Basaltic Lava Flows in Coreholes ICPP-213, ICPP-214, ICPP-215, and USGS 128 Near the Vadose Zone Research Park, Idaho Nuclear Technology and Engineering Center, Idaho National Engineering and Environmental Laboratory, Idaho**



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Cover: Photograph on right is of boxed core. Graphic on left is an artist's rendition of the Earth's geomagnetic field.

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**By Duane E. Champion and Theodore C. Herman**

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Open File Report 03-483

**Prepared in cooperation with the**

**U.S. DEPARTMENT OF ENERGY**

**Idaho Falls, Idaho  
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**U.S. GEOLOGICAL SURVEY**  
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# **Paleomagnetism of Basaltic Lava Flows in Coreholes ICPP-213, ICPP-214, ICPP-215, and USGS 128 Near the Vadose Zone Research Park, Idaho Nuclear Technology and Engineering Center, Idaho National Engineering and Environmental Laboratory, Idaho**

By Duane E. Champion and Theodore C. Herman

## **ABSTRACT**

A paleomagnetic study was conducted on basalt from 41 lava flows represented in about 2,300 ft of core from coreholes ICPP-213, ICPP-214, ICPP-215, and USGS 128. These wells are in the area of the Idaho Nuclear Technology and Engineering Center (INTEC) Vadose Zone Research Park within the Idaho National Engineering and Environmental Laboratory (INEEL). Paleomagnetic measurements were made on 508 samples from the four coreholes, which are compared to each other, and to surface outcrop paleomagnetic data. In general, subhorizontal lines of correlation exist between sediment layers and between basalt layers in the area of the new percolation ponds. Some of the basalt flows and flow sequences are strongly correlative at different depth intervals and represent important stratigraphic unifying elements. Some units pinch out, or thicken or thin even over short separation distances of about 1,500 ft. A more distant correlation of more than 1 mile to corehole USGS 128 is possible for several of the basalt flows, but at greater depth. This is probably due to the broad subsidence of the eastern Snake River Plain centered along its topographic axis located to the south of INEEL. This study shows this most clearly in the oldest portions of the cored sections that have differentially subsided the greatest amount.

## **INTRODUCTION**

Scientists from the U.S. Geological Survey have been studying the petrography, paleomagnetism, and age of basalt lava flows in numerous coreholes at the Idaho National Engineering and Environmental Laboratory (INEEL). The INEEL is located between Arco and Idaho Falls in southeastern Idaho (fig. 1). The current program is a continuation of studies

begun in 1974 to evaluate potential volcanic hazards at INEEL. These studies have included geologic mapping and various studies of surface lava flows such as petrologic and paleomagnetic investigations and radiometric age measurements. Previous investigations also were carried out on selected drill cores from different facilities located within the INEEL.

The present project was begun in Summer, 2000, with the objective of studying, in some detail, core samples from new moderate-depth wells at the Idaho Nuclear Technology and Engineering Center (INTEC) Vadose Zone Research Park located about 2 miles west of the main INTEC Facility within the INEEL. The cores studied include those from wells ICPP-SCI-V-213, ICPP-SCI-V-214, ICPP-SCI-V-215, known in this report hereafter as ICPP-213, ICPP-214 and ICPP-215 respectively, and also well USGS 128. This work was done in consultation with the Applied Geosciences Department of Bechtel-BWXT Idaho, LLC, with the purpose of understanding the basalt stratigraphy of the unsaturated zone near and underneath the new percolation ponds of the Vadose Zone Research Park. A study of the hydraulic properties of the sedimentary interbeds in corehole ICPP-215 has already been published by Perkins (2003). This facility was placed into operation in August, 2002. No bedrock coring of any appreciable depth had previously occurred near this new facility. This information will be used to extend a three-dimensional stratigraphic framework of the INEEL for geologic and hydrologic studies, including the evaluation of potential volcanic and seismic hazards to the INEEL, and the flow of radionuclide-contaminated ground water above and within the Snake River Plain (SRP) aquifer. Funding for this research has been provided by the U.S. Department of Energy, through the INEEL Project Office, Water Resources Discipline, of the U.S. Geological Survey.



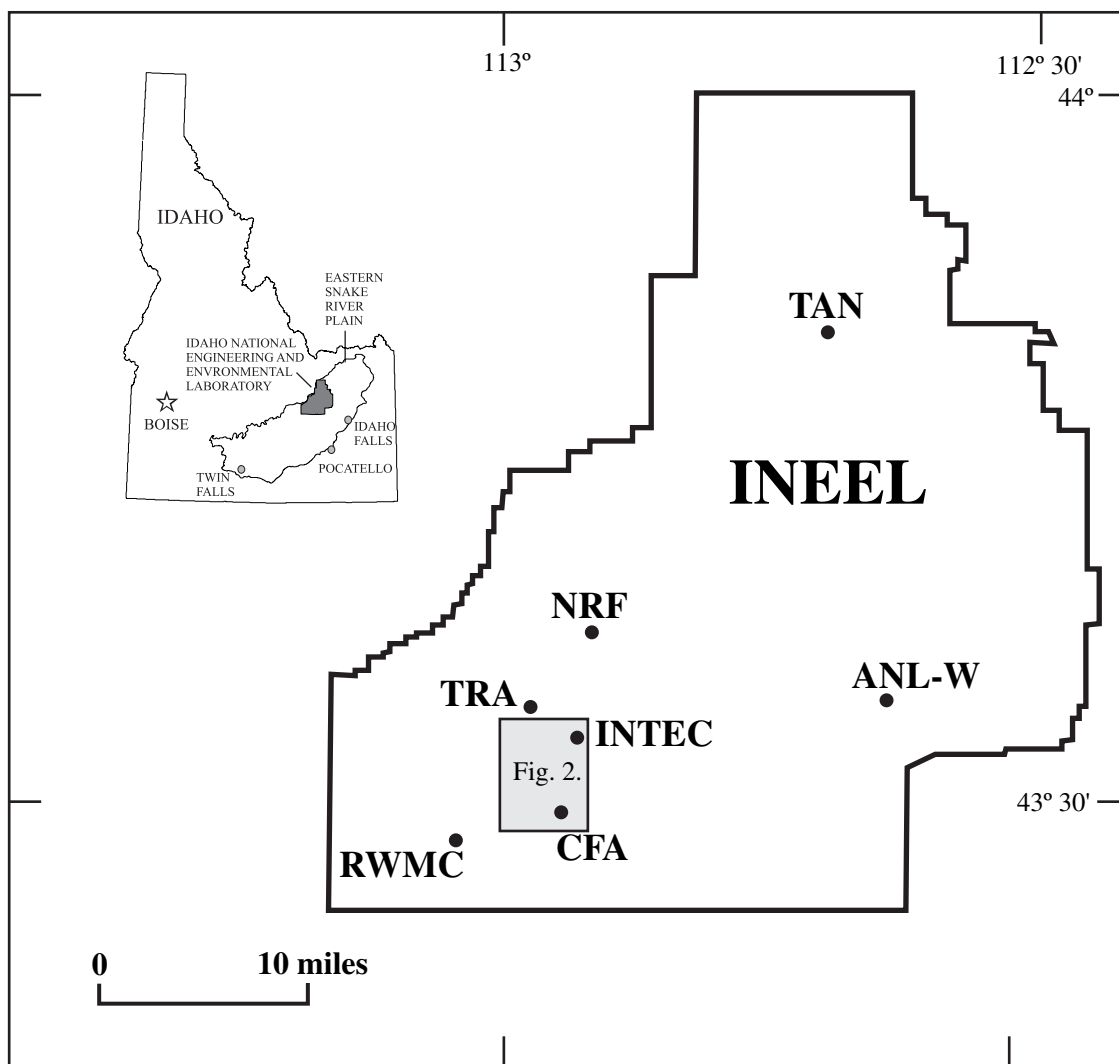


Figure 1. Location map showing the boundary of the Idaho National Engineering and Environmental Laboratory (INEEL), certain facilities areas, and the specific area studied in this investigation.

## GEOLOGIC SETTING

The INEEL covers an area of about 2,300 km<sup>2</sup> in the eastern SRP (fig. 1), which is a northeast-trending structural trough containing Neogene volcanic rocks and interbedded sediments. Tertiary rhyolites are generally exposed only along the margins of the Plain, but several Quaternary rhyolite domes, surrounded by basalt flows, are located in the center of the SRP. Late Pleistocene and Holocene basalt lava fields cover most of the SRP. In particular, the axis of the SRP is a persistent locus of the basalt shield vents from which these young lava flows erupt. Kuntz and others (1994) showed that the surface area of the INEEL is dominated by lava flows of the

Qbb and Qbc relative age classification units, suggesting they are 15 to 400 ka in age.

Lava flows at the INEEL are very similar petrographically. All are tholeiitic olivine basalt that contains olivine, plagioclase, clinopyroxene, ilmenite, magnetite, glass, and accessory apatite. In general, there are significantly different textural varieties between adjacent basalt flows even though the mineralogy remains similar. In the subsurface, silt and sand interbeds separate some lava flows although the distribution and thickness of these interbeds are highly variable. These sedimentary interbeds are particularly common in the subsurface of the INTEC Vadose Zone Research Park.

Surface lava flows and vents in the southern part of the INEEL have normal polarity and were erupted during the

Brunhes Normal Polarity Chron (<780ka). Some surface lava flows and vents in the northern part of the INEEL are reversely magnetized and were erupted during the Matuyama Reversed Polarity Chron (0.78–2.58 Ma). A reversed polarity lava flow unit sequence is sometimes found at moderate (350–500 ft) depths in coreholes from the southern INEEL area, and has been identified as the Big Lost Polarity Subchron by Champion and others (1988). This sequence was not found in any of the wells described in the current study.

## ANALYTICAL TECHNIQUES

The drill cores from wells ICPP-213, -214, -215, and USGS 128 were carefully logged and sampled using Lithologic Core Storage Library protocols described in Davis and others (1997). Prior to sampling, we described the core material and located the tops and bottoms of lava flows. Depths were measured by tape measure from known marks recorded on wooden plugs in the core boxes. These wooden plugs are placed by the drillers at the time of coring, and record the measured depths logged at the end of each coring run. This study doesn't include the detailed depth, thickness and petrographic descriptions that are part of many of our previous studies; nor were any conventional K-Ar or  $^{40}\text{Ar}/^{39}\text{Ar}$  ages produced as part of this study.

For paleomagnetic studies, seven samples of core were used from each lava flow unit that was identified by inspection. For each sample, a 2.5-cm diameter core was drilled at right angles to the axis of the original core to provide material for paleomagnetic analysis. The coreholes are a priori assumed to be vertical in their original drilling orientation to facilitate paleomagnetic study. Gyroscopic deviation logs of wells ICPP-215 and USGS 128 were made at 10-ft intervals, and they document modest deviations, no greater than 2.2 and 1.3° respectively, from vertical for those coreholes. Typical deviation from vertical for INEEL coreholes is less than one degree, and is thus no impediment to paleomagnetic remanent inclination interpretations. The samples were trimmed to 2.2-cm lengths, and the inclination and intensity of magnetization were measured with a cryogenic magnetometer. Progressive alternating-field demagnetization using a commercial tumbling demagnetizer was performed on each specimen to remove any components of secondary magnetization. The primary or characteristic remanent inclinations measured on individual basalt specimens are shown on the logs for the cores studied in figures 3–6. Mean inclination values for each lava flow, and 95 percent confidence limits about the mean value were calculated using the method of McFadden and Reid (1982).

## PALEOMAGNETIC RESULTS

Forty-one lava flows were identified and enumerated in the four cored holes, ICPP-213, -214, -215, and USGS 128, that were studied paleomagnetically (fig. 2). The flows are numbered in ascending order with depth for each corehole studied; the numbers only indicate stratigraphic order within that corehole and do not necessarily indicate correlation to an identically numbered flow in a nearby corehole. The 41 lava flows range in thickness from 9 to more than 197 ft, and are composed of one to typically two or more flow units. Individual flow units are usually 5 to 20 ft in thickness, with sequences of several thin flow units indicating some proximity to the vent area for that flow group. On the other hand, a flow unit of greater than average thickness (more than 30 ft) is assumed to be a ponded, or inflated, flow that accumulated in a depression where the outlet was restricted or blocked. These depressions may have formed in strictly geomorphic ways, such as a closed basin between several shield volcanoes, or a depression along the course of an ephemeral stream. They may have formed due to topography created by earlier lava flows of the same eruption of which they are part. The depressions may also have formed in structural ways, such as slumping of surface rocks in volcanic rift zones, slumping related to compaction of underlying sedimentary or volcanic deposits, or perhaps, faulting.

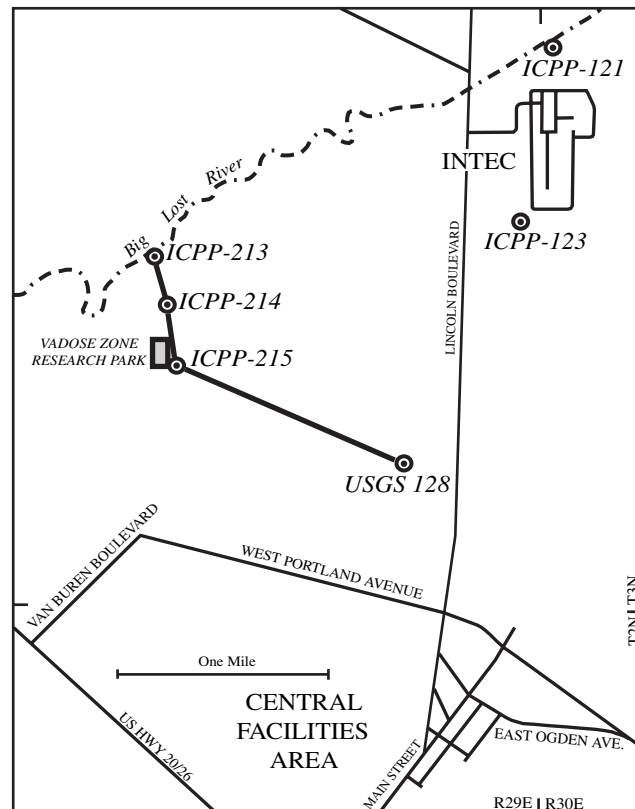


Figure 2. Location map of the southern INEEL area showing well and facility locations, roads, and the course of the Big Lost River. Line of cross section of figure 7 shown as solid line.

#### 4 Paleomagnetism of Basaltic Lava Flows in Coreholes ICPP-213, ICPP-214, ICPP-215, and USGS 128

Most flows investigated in this study do not have significant amounts of cinder, breccia, or rubble at or near their uppermost surfaces. This suggests that most of the flows are pahoehoe and not slab pahoehoe or aa flows in morphology. Basaltic lava flows of the eastern SRP are remarkably similar in gross petrographic character. Nonetheless, some petrographic characteristics were noted in the present study for the different lava flows, and were used to establish boundaries of major significance between these flows. These petrographic assessments are qualitative in nature, and in no way replace any future quantitative chemical and petrographic studies of these coreholes.

Paleomagnetic measurements were made on 508 basalt samples from the four coreholes. All 41 lava flows have remanent magnetization of normal polarity, presumably acquired during the Brunhes Normal Polarity Chron, and therefore are all younger than 0.78 Ma. The averaged mean inclination values for individual lava flows or flow unit groups varied between  $50.5$  to  $77.4^\circ$ , within the usual range of inclination due to geomagnetic secular variation. The precision of these mean values, reported as two standard errors of the mean ( $\alpha_{05}$ ), ranges between  $0.6$  to  $6.1^\circ$ ; the modal value is near  $2^\circ$ . Data of this precision allow us to differentiate and correlate flows or flow units, when combined with the stratigraphic constraints from the physical core logging, and the qualitative petrographic assessments.

Similar mean inclination values can be randomly acquired by two successive lava flows, even though they are tens of thousands of years different in age. Conclusions from the similar inclinations requiring they be similar in age would then be in error. Flows of differing lithology having the same mean inclination value, and which are not separated by a sedimentary interbed, may well represent the same eruptive event in time, but may have been erupted from two distinct vents and thus represent two different co-erupting magma batches. Such circumstances have been demonstrated in the surface paleomagnetic and petrographic/chemical work presented in Kuntz and others (2002). The paleomagnetic study presented in this report did not always allow a clear choice between these interpretative alternatives.

The results for individual core holes are discussed below.

##### Well ICPP-213

Well ICPP-213, completed in September, 2000, is a 560-ft-deep corehole located 2,500 ft north of the INTEC Vadose Zone Research Park, and close to the channel of the Big Lost River. Well ICPP-213 contains nine lava flows separated by eolian and alluvial sedimentary interbeds. A log of the core stratigraphy, paleomagnetic inclinations, and the depths of samples used for paleomagnetic measurements is given in figure 3. The stratigraphy, mean inclination values with uncertainties, and depth ranges for well ICPP-213 are given in table 1. Notes regarding the stratigraphy and paleomagnetic study of the corehole include:

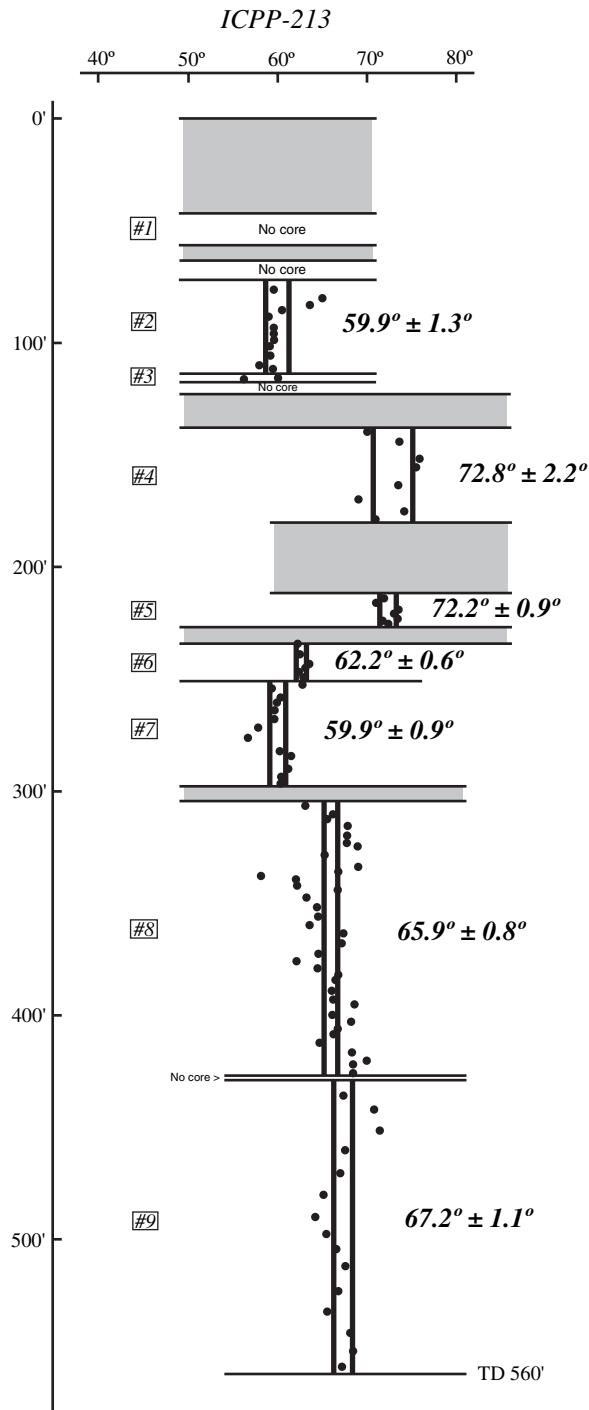


Figure 3. Plot of core stratigraphy, paleomagnetic sample location, and mean paleoinclination values and uncertainties for corehole ICPP-213. Shading represents sedimentary interbeds, horizontal lines are flow contacts or uncored intervals, and solid data points show depths and inclination values of individual samples. Vertical lines in stratigraphic intervals of lava flows are 95 percent confidence limits around the mean inclination values of those intervals.

- Flow 1—The gamma log for this corehole indicates a lava flow exists between depths of 42 to 56 ft and it was rotary drilled through without coring. This uncored flow may be the young (approximately 50 ka) flow from Quaking Aspen Butte which disappears under recent Big Lost River sedimentary deposits at the location of the visitor rest area on US Hwy 20.
- Flow 2—is composed of two flow units, approximately 36- and 12-ft thick; the core recovery of the top of the upper flow unit was poor, as noted by gamma log. Though a thin approximately 1-ft layer of black sand was found at 92-ft depths in the core boxes, it occurs within the massive core of the 36-ft thick flow unit, and is viewed as “trickle-down sediment” from layers higher in the cored section.
- Flow 3—is composed of a single flow unit, approximately 9-ft thick, and is identified by a reddish top and soil carbonate (caliche?) which possibly indicates sustained exposure to weathering in the surface environment. From gamma log record it seems the bottom 5 ft of this flow was incompletely recovered in coring. The indicated paleoinclination values for two samples taken high in this flow are very similar in value to overlying flow 2, and are viewed as thermally overprinted in magnetic character by flow 2. Chemical and/or petrographic study of this thin flow will verify if this view is correct, or if this is just an earlier flow unit part of flow 2.
- Flow 4—is composed of a single 43-ft thick flow unit. It rests between two thick sedimentary interbeds.
- Flow 5—is composed of a single 15-ft thick flow unit.
- Flow 6—is composed of three flow units, 10-, 2- and 5-ft thick. These flow units are notable in hand specimen as rich in larger than average plagioclase phenocrysts.
- Flow 7—is composed of two flow units, 13- and 34-ft thick. These flow units are notable in hand specimen as rich in larger than average olivine phenocrysts.
- Flow 8—is composed of 14 flow units, ranging from 2- to 24-ft thicknesses, and aggregates to a total 123-ft thick. Such a thick, thin-bedded, flow unit group is usually thought to be located close to its source vent. In addition, a flow unit at 378- to 398-ft depths is composed of remobilized spatter, a basalt texture found typically within a kilometer of its source. This spatter was briefly projected into the air by the eruption, causing instantaneous oxidation (reddening) and vesiculation of the basalt lava. When this occurs during high rates of effusion of the source vent, the spatter may remobilize and flow away from the vent as a lava flow. But, the magmatic gases and heat lost to the brief ballistic history of this lava increase its viscosity so that it usually doesn't flow far before freezing. This flow

group ends with flow units having larger than average plagioclase, but that texture is not uniform for the entire sequence.

- Flow 9—is composed of two flow units, 3- and at least 128-ft thick. The exceptional thickness of the deeper flow unit requires some unusual and unknown explanation. Topography to contain a basalt flow, such that it would inflate to more than 120 ft in thickness, is rare to nonexistent on the present eastern SRP, unless the flow was extraordinarily voluminous. Additional coring to examine its lateral extent could be valuable to the hydrologic modeling of the eastern SRP aquifer. The great thickness and massive character of this flow unit suggest that its hydraulic conductivity is much lower than that of other flows, possibly forming a significant permeability contrast of unknown lateral extent near the base of the unsaturated zone. The upper boundary of the flow was identified by a thin lost core interval, but the definition may be in error. The similar mean inclination of this flow and of flow 8 suggests that they may be essentially identical in age. Chemical, petrographic, and argon age data should verify or deny the assumed independence of flows 8 and 9 taken by this study.

## Well ICPP-214

Well ICPP-214, completed in May, 2001, is a 503-ft-deep corehole located 1,300 ft north of the INTEC Vadose Zone Research Park. Well ICPP-214 contains eight lava flows separated by eolian and alluvial sedimentary interbeds. A log of the core stratigraphy, paleomagnetic inclinations, and the depths of samples used for paleomagnetic measurements is given in figure 4. The stratigraphy, mean inclination values with uncertainties, and depth ranges for well ICPP-214 are given in table 2. Notes regarding the stratigraphy and paleomagnetic study of the corehole include:

- Flow 1—is composed of a single 53-ft thick flow unit. The gamma log indicates that the top of this lava flow is at approximately 53-ft depth though coring was not begun until 55-ft depth. A lost core interval of 1 ft occurred at 93-ft depth, but is within a massive, unvesiculated flow and not thought to be any boundary.
- Flow 2—is composed of four flow units, ranging from 3 to 9 ft thicknesses. This flow unit group lies on an 18-ft thick sedimentary interbed, with an 8-ft interval of lost and unrecovered core. The gamma log suggests the lost interval is sedimentary, and not lava flow in character.
- Flow 3—is composed of three flow units, 4-, 16-, and 2-ft thick.

## 6 Paleomagnetism of Basaltic Lava Flows in Coreholes ICPP-213, ICPP-214, ICPP-215, and USGS 128

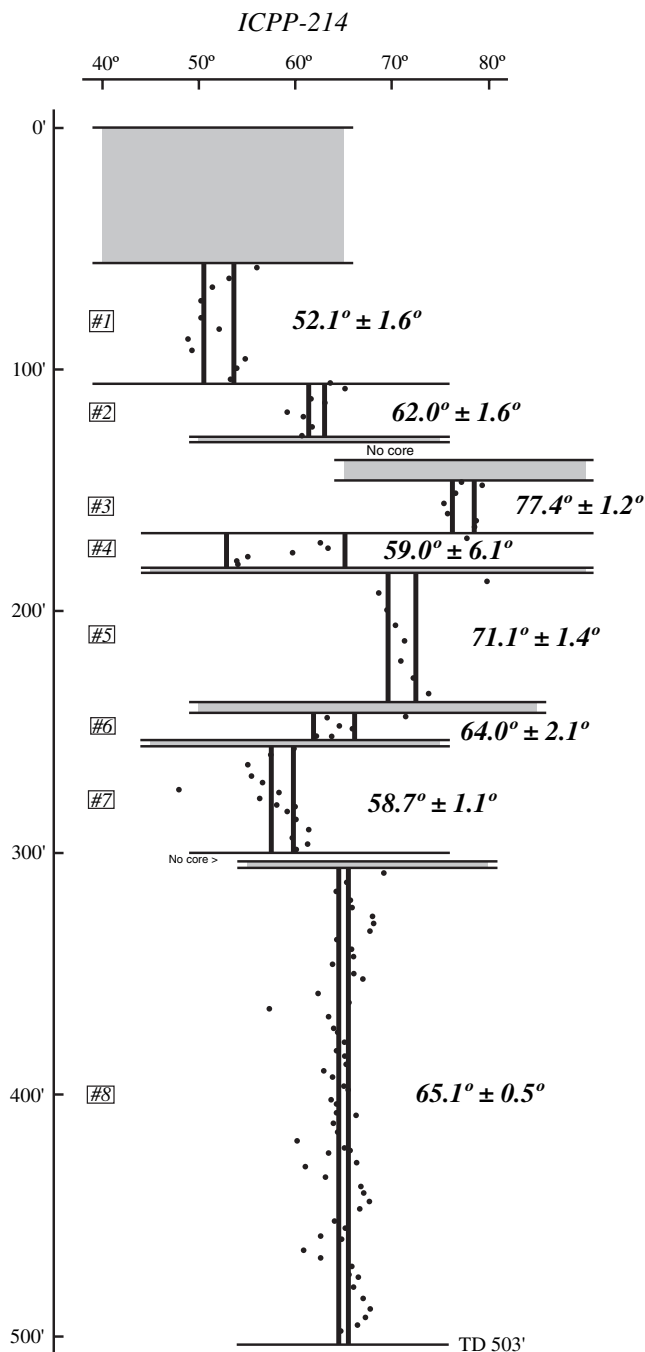


Figure 4. Plot of core stratigraphy, paleomagnetic sample location, and mean paleoinclination values and uncertainties for corehole ICPP-214. Symbols the same as figure 3.

- Flow 4—is composed of a single 14-ft thick flow unit. The top surface of this flow contains carbonate material (caliche?), and its texture is rather aphanitic compared to average eastern SRP tholeiite textures. Also, the gamma log of this depth interval shows elevated base levels indicating that this lava flow has higher  $K_2O$ , and a stronger natural gamma signature. Reed and others

(1997), and Hughes and others (2002) have noted a high  $K_2O$  lava flow usually found at approximately 150 ft depths in the subsurface of the INTEC area, that would correlate to this depth interval. The mean inclination value of flow 4 has much larger uncertainty than usual. Flow 3 completely overprinted the magnetization of a sample taken 2 ft below the upper surface of flow 4, and deeper samples have progressively shallower values ending at inclinations of about 54°, suggesting some thermal overprinting even at deeper levels. If the thermal overprint from flow 3 has a much deeper penetration than typical, then the best inclination estimate of flow 4 may be that of its deepest samples. It is likely that corehole ICPP-214 happens to sample flow 3 along an internal flow pathway, through which many cubic meters of 1,100°C lava passed. The pathway would heat underlying flow 4 to unusual depths and cause the severe magnetic overprints found.

- Flow 5—is composed of a single 51-ft thick flow unit.
- Flow 6—is composed of a single 11-ft thick flow unit. It rests between two thin sedimentary interbeds. This flow unit is notable in hand specimen as rich in larger than average plagioclase phenocrysts.
- Flow 7—is composed of five flow units, ranging from 2 to 20 ft thicknesses. They rest between two thin sedimentary interbeds. These flow units are notable in hand specimen as rich in larger than average olivine phenocrysts.
- Flow 8—is composed of at least 16 flow units, ranging from 1- to 26-ft thicknesses, and aggregates to a total of at least 197-ft thick. At the 503-ft total depth (TD) a lost core interval may suggest a major flow boundary, but the gamma log for the corehole indicates no sediment yet at 500-ft depth, so the flow group may be even thicker. Such a thick, thin-bedded, flow unit group is usually taken to be located close to its source vent. This flow group ends with flow units having larger than average plagioclase, but that texture is not uniform for the entire sequence.

### Well ICPP-215

Well ICPP-215, completed in May, 2001, is a 503-ft-deep corehole located 200 ft southeast of the INTEC Vadose Zone Research Park. Well ICPP-215 contains eight lava flows separated by eolian and alluvial sedimentary interbeds. A log of the core stratigraphy, paleomagnetic inclinations, and the depths of samples used for paleomagnetic measurements is given in figure 5. The stratigraphy, mean inclination values with uncertainties, and depth ranges for well ICPP-215 are given in table 3. Notes regarding the stratigraphy and paleomagnetic study of the corehole include:

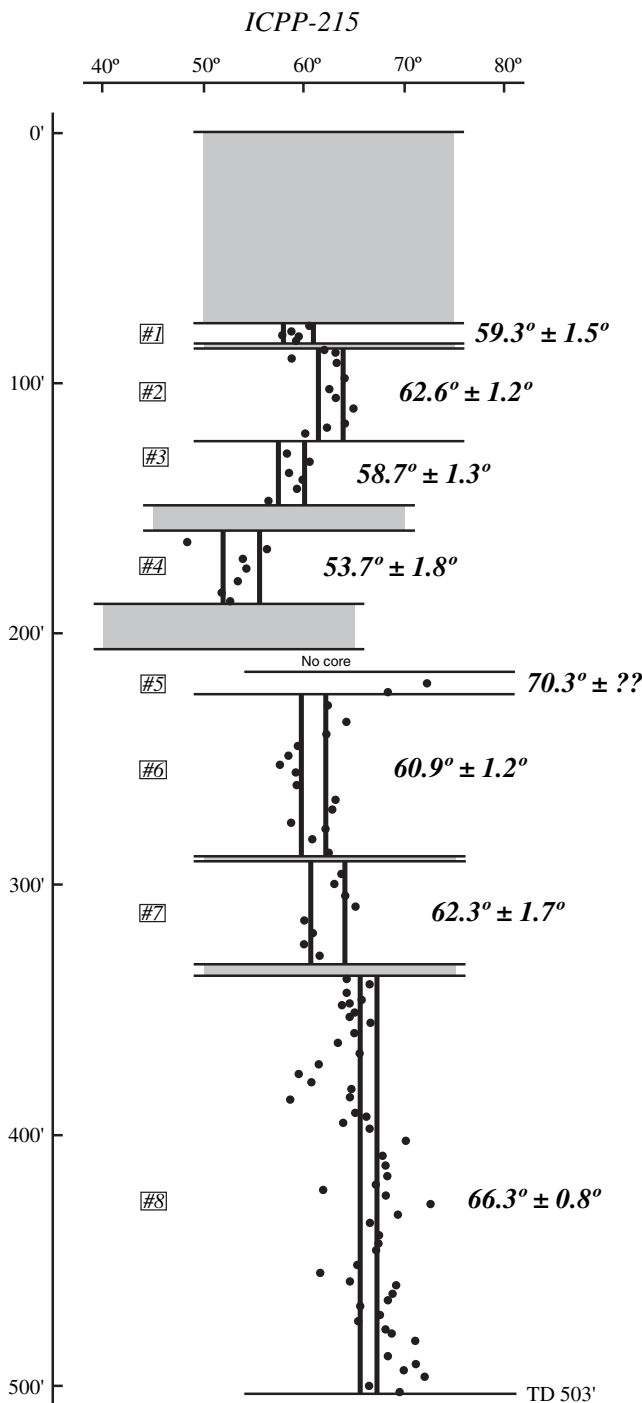


Figure 5. Plot of core stratigraphy, paleomagnetic sample location, and mean paleoinclination values and uncertainties for corehole ICPP-215. Symbols the same as figure 3.

- Flow 1—is composed of a single 8-ft thick flow unit. In hand specimen this flow has a “felty” fabric of abundant, fine plagioclase crystals, with olivine clots.

- Flow 2—is composed of two flow units, 10- and 27-ft thick. It lies between two very thin sedimentary interbeds.
- Flow 3—is composed of a single 26-ft thick flow unit. The top 6 ft of this lava flow is stored within Lexan tubing, and was examined only through the plastic. In hand specimen this flow has a “felty” fabric of fine plagioclase crystals, with olivine phenocrysts as well.
- Flow 4—is composed of a single 29-ft thick flow unit. It lies between two thick sedimentary interbeds, the upper of which was incompletely recovered as core. In hand specimen the texture of this flow is aphanitic and unusual for an eastern SRP tholeiite. The gamma log for corehole ICPP-215 shows a very elevated base level for this flow, such that it almost can’t be recognized as basalt lava compared to the typically high gamma signals from the enclosing sedimentary layers. The strong natural gamma signal probably arises from higher than usual  $K_2O$  for this lava flow. Reed and others (1997) and Hughes and others (2002) have noted a high  $K_2O$  lava flow usually found at ~150-ft depths in the subsurface of the INTEC area, that would correlate to this depth interval.
- Flow 5—is composed of a single 9-ft thick flow unit. It underlies a thick sedimentary interbed, the bottom 4 ft of which were incompletely recovered as core. This flow was not initially recognized in our physical logging of corehole ICPP-215. High paleoinclination values, coupled with the observation that in texture the flow has some olivine content despite being fine-grained overall and quite different than the underlying flow, sparked its identification. Only two samples were taken from this flow with a mean inclination value of 70.3°; such a small sample population does not allow uncertainty statistics to be calculated.
- Flow 6—is composed of three flow units, 27-, 7-, and 31-ft thick. These flow units are notable in hand specimen as rich in larger than average plagioclase phenocrysts.
- Flow 7—is composed of a single 41-ft thick flow unit. It lies between two thin sedimentary interbeds, the lower of which was incompletely recovered as core. This flow is notable in hand specimen as rich in larger than average olivine phenocrysts.
- Flow 8—is composed of at least 16 flow units, ranging from 1- to 24-ft thicknesses, and aggregates to a total of at least 166-ft thick. At the 503 ft TD corehole ICPP-215 is still within a thick flow unit, so the flow group may be even thicker. Such a thick, thin-bedded, flow unit group is probably located close to its source vent. This flow group ends with a flow unit having larger than average plagioclase, but that texture is not uniform for the entire sequence.



## Well USGS 128

Well USGS 128, completed in August, 2002, is a 768-ft deep corehole located about 6,400 ft southeast of the INTEC Vadoso Zone Research Park, and close to Lincoln Boulevard about halfway between INTEC and the Central Facilities Area (CFA). It was drilled to replace a damaged monitoring well CFA LF 3-11, but cored deeper than necessary to maximize stratigraphic information returned from this location. Well USGS 128 contains 16 lava flows separated by eolian and alluvial sedimentary interbeds. A log of the core stratigraphy, paleomagnetic inclinations, and the depths of samples used for paleomagnetic measurements is given in figure 6. The stratigraphy, mean inclination values with uncertainties, and depth ranges for well USGS 128 are given in table 4. Notes regarding the stratigraphy and paleomagnetic study of the corehole include:

- Flow 1—is composed of four flow units, ranging from 1- to 16-ft thick. In hand specimen, some plagioclase is evident as phenocrysts in this lava flow.
- Flow 2—is composed of a single 52-ft thick flow unit. In hand specimen, some olivine is evident as phenocrysts in this lava flow. The uppermost paleomagnetic sample was completely overprinted by flow 1, but deeper samples record a different paleoinclination.
- Flow 3—is composed of three flow units, 4-, 1-, and 37-ft thick. In hand specimen, olivine is evident as phenocrysts in this lava flow.
- Flow 4—is composed of a single 36-ft thick flow unit. It lies between two sedimentary interbeds, the lower of which was incompletely recovered as core. In hand specimen the texture of this flow is aphanitic and unusual for an eastern SRP tholeiite. The gamma log for corehole USGS 128 shows a very elevated base level for this flow, almost 50 percent of the typically high gamma signals from the enclosing sedimentary layers. The strong natural gamma signal probably arises from higher than usual  $K_2O$  for this lava flow. Reed and others (1997) and Hughes and others (2002) have noted a high  $K_2O$  lava flow usually found at approximately 150 ft depths in the subsurface of the INTEC area, that would correlate to this depth interval.
- Flow 5—is composed of a single 49-ft thick flow unit. It lies between two sedimentary interbeds. In hand specimen, some olivine is evident as phenocrysts in this lava flow.
- Flow 6—is composed of three flow units, 25-, 7-, and 3-ft thick. These flow units are notable in hand specimen as rich in larger than average plagioclase phenocrysts.

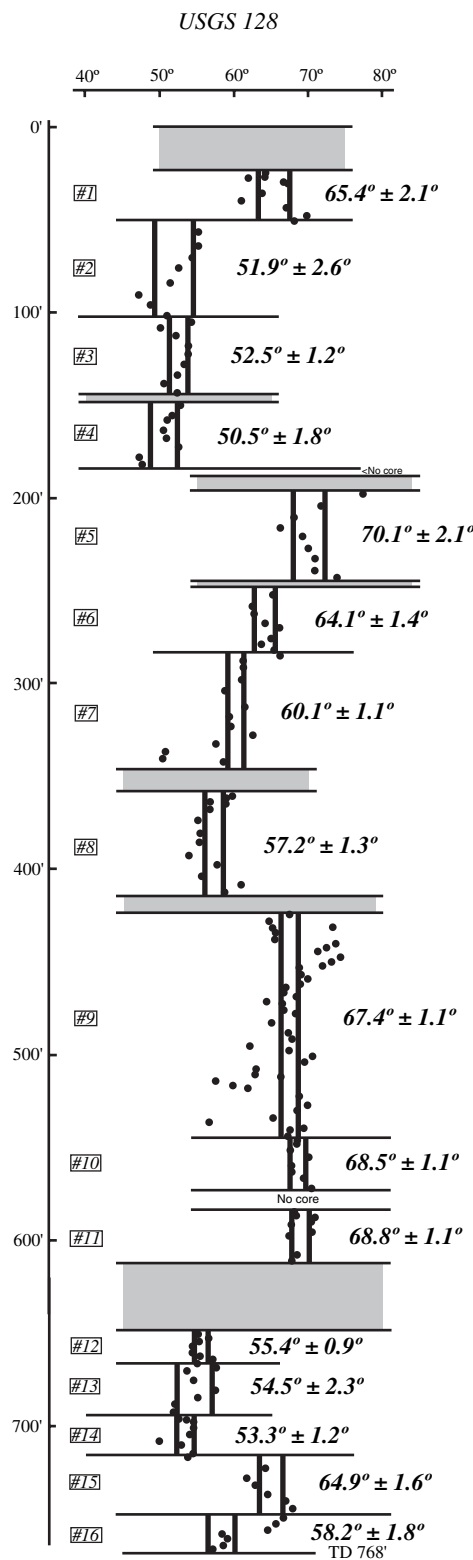


Figure 6. Plot of core stratigraphy, paleomagnetic sample location, and mean paleoinclination values and uncertainties for corehole USGS 128. Symbols the same as figure 3.

- Flow 7—is composed of three flow units, 53-, 8-, and 3-ft thick. These flow units are notable in hand specimen as rich in larger than average olivine phenocrysts.
- Flow 8—is composed of three flow units, 10-, 3-, and 43-ft thick. It lies between two thick sedimentary interbeds, the upper of which is incompletely recovered over a 4-ft span. In hand specimen, some olivine and plagioclase are evident as phenocrysts in this lava flow.
- Flow 9—is composed of 14 flow units, ranging from 1- to 26-ft thicknesses, and aggregates to a total of 122-ft thick. Such a thick, thin-bedded, flow unit group is usually taken to be located close to its source vent. In hand specimen this group has various textural aspects.
- Flow 10—is composed of two flow units, 21- and 7-ft thick. Apart from the appearance of the top of this flow as a major break from the overlying flow 9 there are no distinguishing differences between the two flows. The paleoinclination value for this flow is essentially identical to that of flow 9, suggesting they may not be different in age.
- Flow 11—is composed of two flow units, both about 14-ft thick. The flow is overlain by an 11-ft thick unrecovered core interval, and underlain by a thick sedimentary interbed, composed of clay, silt, sand and gravel, which also was incompletely recovered as core. The lower flow unit has a rubble aspect, which also interfered with the complete recovery of that flow interval. The gamma log for corehole USGS 128 shows some signal above basalt base level for the overlying uncored interval to flow 11 suggesting some sediment content for this depth interval. This possible sediment may be “trickle-down” from true sediment interbeds higher in the section, or represent a major break in time. The paleoinclination value for this flow is essentially identical to that of flows 9 and 10, suggesting it may not be different in age than the two overlying flows. A chemical and/or petrographic evaluation of these three flows would assist answering this question.
- Flow 12—is composed of three flow units, 9-, 5-, and 3-ft thick. These flow units are notable in hand specimen as rich in larger than average plagioclase phenocrysts. This petrographic aspect is the principal reason this flow is separated from underlying flows.
- Flow 13—is composed of a single 28-ft thick flow unit. Apart from the petrographic differences between the top of this flow and the overlying flow 12 there are no other distinguishing differences between the two flows. Also, the paleoinclination value for this flow is essentially identical to that of flow 12, suggesting they may not be different in age.
- Flow 14—is composed of three flow units, 7-, 1-, and 12-ft thick. This flow has a significantly reddened top, and overlies a 1-ft thick lost core interval, which shows signs of clay as crack fillings. Other than the red top, there are no distinguishing differences between this flow and overlying flow 13. The paleoinclination value for this flow is essentially identical to that of flows 12 and 13, suggesting it may not be different in age than the two overlying flows. A chemical and/or petrographic evaluation of these three flows would assist in answering this question.
- Flow 15—is composed of a single 31-ft thick flow unit. Clay is found in cracks in the top of this flow, and the gamma log for corehole USGS 128 shows three sharp natural gamma spikes between 715 and 725 ft depths, which are attributed to sediment infilling. In hand specimen, olivine is evident as phenocrysts in this flow. The uppermost paleomagnetic sample was completely overprinted by flow 14, but deeper samples record a different paleoinclination.
- Flow 16—is composed of two flow units, 19- and 2-ft thick. The top of this flow is reddened, contains silt infill, and is petrographically distinct from overlying flow 15. The uppermost three paleomagnetic samples were completely overprinted by flow 15, but deeper samples record a somewhat different paleoinclination. During the physical examination of this corehole in the Core Library the flow unit boundary at 766 ft was considered a possible major time break. The termination of coring at 768 ft TD prevents a paleomagnetic evaluation of this possibility.

## DISCUSSION

Paleomagnetic inclination determinations document that 41 lava flows were identified in coreholes ICPP-213, -214, -215, and USGS 128. All flows have normal magnetic polarity and erupted during the Brunhes Normal Polarity Chron which has existed since 0.78 Ma. Figure 7 is a qualitative representation of a vertical line of cross section constructed through these four coreholes showing the relative proximity of the three ICPP coreholes near the Vadose Zone Research Park, and the twice farther gap to corehole USGS 128. Lines of correlation of either thin sedimentary interbeds, or the upper and lower surfaces of thick sedimentary interbeds and lava flows have been drawn between the coreholes. The parallel fabric of subhorizontal correlation between these wells is an essential conclusion of this report, but the deviations in detail are also informative.

Fluvial silts, sands, and gravels along the course of the Big Lost River, a zone that can be up to 4 miles wide in places, mask the uppermost flows sampled near the new percolation ponds, with a thickness of almost 80 ft in corehole ICPP-215. The thickness of surficial sediment was described by Anderson and others (1996a), and their figure 7 depicts the variation of



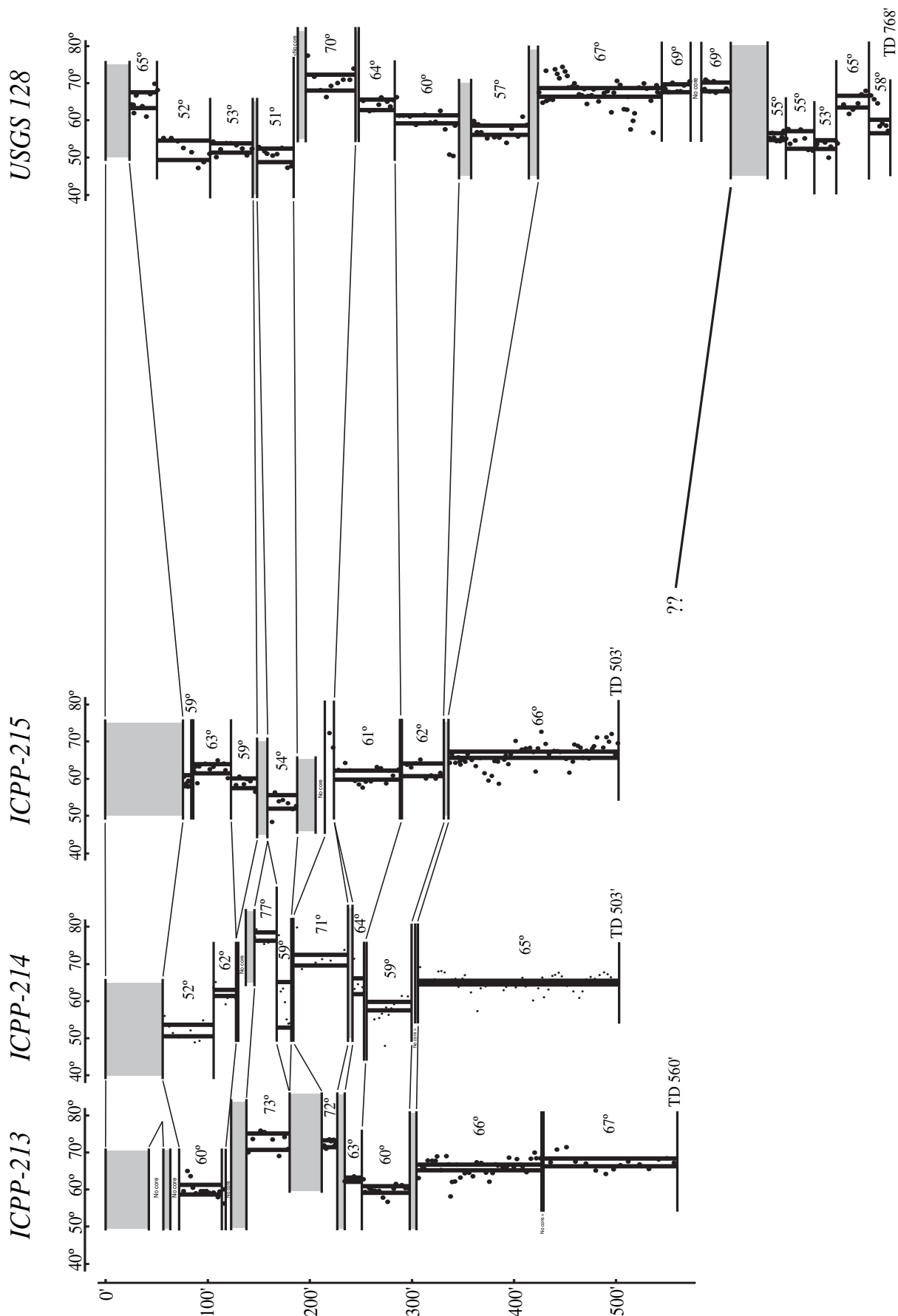


Figure 7. Cross section drawn between wells ICPP-213, -214, -215, and USGS 128. Section is qualitative and not drawn strictly to scale; total horizontal distance is about 3km. Vertical exaggeration is approximately a factor of 15.

thickness across the southern INEEL area. The thinner surface sediments at the location of USGS 128 allow us to correlate the 65° inclination of flow 1 in that well to flows from Hill 5206 located near the southern boundary of INEEL, just north of Big Southern Butte. This shield produced 64° inclination lava flows which dominate the surface at RWMC, EBR, and for much of the CFA areas. The approximate 52° paleoinclinations of flows 2 and 3 in corehole USGS 128, by paleoinclination correlation to wells farther east, suggest that those flows may come from Mid Butte and a vent at the west base of Middle Butte (Lanphere and others, 1993). Chemical or petrographic correlation to those vents would support this conclusion.

Some correlation may exist between the uppermost flows of coreholes ICPP-213, -214, and -215. Flows numbered 2 in all three wells have paleoinclination values between 60 and 63°, and thus correlate. Flows 1 and 3 in corehole ICPP-215 share 59° inclinations and are also little different in paleomagnetic character, but are separated by thin sediment interbeds and another lava flow, typically denoting significant passage of time. No correlation in upper flows seems to exist between coreholes ICPP-215 and USGS 128, nor is there an easy tie for the 52° inclination in corehole ICPP-214 to either corehole ICPP-213 or ICPP-215. Finally, the uncored flow 1 in corehole ICPP-213 may be the 64° inclination flow from Quaking Aspen Butte, which disappears beneath the fluvial sediments of the Big Lost River about 2 miles to the west. Further paleomagnetic study of short coreholes taken near ICPP-213 which sample this depth interval may answer that question.

The first unit that appears for certain in stratigraphic correlative unity among all four coreholes is a sedimentary interbed found at depths between 130 to 150 ft, which seems to gently increase in depth north to south. Between it and another unifying sedimentary interbed at 180 to 200 ft depths lie two distinctive lava flows. Flow 4 in ICPP-213 and flow 3 in ICPP-214 have steep paleoinclination values at similar depths. Flows numbered 4 in ICPP-214, -215, and USGS 128 all have the unique aphanitic texture, high gamma log signals, and paleoinclination values in the low 50's associated with the high K<sub>2</sub>O flow of Reed and others (1997). The sequence of flows in corehole ICPP-214 makes it clear that the aphanitic, high K<sub>2</sub>O flow precedes the steep inclination flow in time. The absence of sediment between them suggests they are of similar overall age. The variation in thickness of these two flows from corehole to corehole indicates that the steep inclination flow comes from vents north and west of the Vadose Zone Research Park location, whereas the high K<sub>2</sub>O flow comes from the south.

Immediately underlying the 180- to 200-ft interbed in all four coreholes is another flow, numbered as flow 5 in all wells, with steeper than average paleoinclination values between 70 and 72°. It was previously understood that there were two steep inclination flows of about the same age in the moderate depth subsurface of the INTEC-CFA area, but how they related stratigraphically was not known. Both flows can be found in coreholes ICPP-213 and -214 and in ICPP-214 they are separated by the aphanitic high K<sub>2</sub>O flow. A modest olivine content for the rock in hand specimen is the principal reason the

thin 9-ft thick flow unit was identified in corehole ICPP-215. These flows, numbered 5, thicken in coreholes located east of the study area and were determined by Champion and others (1988) to come from a vent called Hill 5252 located just north of Middle Butte and just south of US Hwy 20. The vent was dated by conventional K-Ar at 350±40 ka (Kuntz and others, 1994). The varying flow thickness in the cross section of figure 7 suggests that Hill 5252 flows moved downhill to the northwest out onto the former floodplain of the Big Lost River, and are thin or thick as determined by ponding and inflation processes that occurred on the irregular fluvial surface. In all probability this flow would not be found much farther to the northwest in coreholes in the Test Reactor Area (TRA).

Flows numbered 6 and 7 in all four coreholes both represent examples of correlation through the entire line of section. Flows numbered 6 have paleoinclination values between 61 and 64° and are distinctly phyrlic in plagioclase, while flows numbered 7 have inclination values between 59 and 62° and are distinctly phyrlic in olivine. The two flows are separated by thin sediment interbeds in coreholes ICPP-214 and -215, so they must be somewhat different in age. No source vent for either of these flows has been identified, but they vaguely thicken to the southeast in the line of cross section of figure 7.

Both flows are found in corehole ICPP-123 (Lanphere and others, 1993), and the plagioclase-phyric flow is found 5 miles east in corehole NPR Test (Champion and others, 1988); these facts suggest that both the flows numbered 6 and 7 erupted from vents located to the southeast of the present study area.

Flow number 8 in corehole USGS 128 does not seem to have any correlative lava flow in the other studied coreholes, with its paleoinclination value of 57° and an average petrographic texture. A possible paleoinclination correlative basalt flow is found in the same depth range in corehole 123, which is located a mile to the northeast, and that flow is K-Ar dated at 466±39 ka (Lanphere and others, 1993). Petrographic and chemical studies would help to confirm this correlation.

Flows with tops trending north to south at depths of 300 ft, to 310 ft, to 340 ft, and finally down to 425 ft, and numbered either 8 or 9 depending on the corehole, represent a major deep zone of correlation in this area of the INEEL. All the flows underlie a thin sedimentary bed which also descends in depth to the south. All the paleoinclination values for these flows range from 65 to 67°, and each is composed of numerous thin basalt flow units. The uppermost flow units in these flow groups have evident plagioclase phenocrysts as part of their petrographic texture, but this characteristic is not clear in lower flow units of the sequences. In coreholes ICPP-214 and -215 these flow groups continue all the way down to their respective TD.

In corehole ICPP-213, flow 8 is underlain by the extremely thick flow 9 which has paleoinclination only 1° steeper than flow 8. Flow 9 was differentiated principally owing to its great thickness, but it may not be from a different eruption than that which produced the multiple flow units of flow 8. In a similar manner, flows 10 and 11 in corehole USGS 128 have paleoinclination values only 1° steeper than overlying flow 9. These flows were differentiated due to their rather greater

thicknesses compared to overlying thin flow units, but may also not be different in eruptive age. In all four coreholes, flows numbered 8 through 11 show slight shallowing in inclination value as one moves up the respective sections. This suggests these flow sequences correlate and demonstrates that some number of decades may have passed while they were forming. Geomagnetic secular variation requires such a timeframe to move the local magnetic vector shallow in inclination by several degrees; such remanent magnetic changes are not usually witnessed in thick eastern SRP flow sequences.

Correlation of this flow sequence can be made to corehole ICPP-123 (fig. 2) at similar depths, similar paleoinclination values, and with similar shallowing paleoinclination with depth (Lanphere and others, 1993). This sequence has an argon age of about 620 ka (Champion and others, 2002), and has been correlated farther to the east to corehole NPR Test, and to the northeast to corehole ICPP-121 (fig. 2). Consequently, this broadly correlative zone of lava flows, positioned deep in the unsaturated zone under the INTEC and CFA areas, has great unifying stratigraphic value. Other basalt flows may appear and disappear from the subsurface sequence, but the continuous units provide stratigraphic continuity.

The thick flow 9 in corehole ICPP-213, and to some extent the thicker flows 10 and 11 in corehole USGS 128, are taken to represent the early products of this enduring eruption when effusion rates would have been typically high. High effusion rates generally allow thicker and longer flows to form. The flows produced by a vent may either run long distances in modest thickness, or pond and fill in depressions in the local topography. Flow 9 in corehole ICPP-213 is taken to be one of these infillings and thus relatively close to the vent location. The entire sequence thins to the southeast suggesting that lava flowed in that direction, but the incomplete coring of the sequence in the coreholes near the Vadose Zone Research Park limits the certainty of that observation.

The great thickness of flow 9 in corehole ICPP-213 presents important localized constraints on movement of waters in the subsurface. Though the flow cracked and contracted 2–3 percent in volume upon cooling, thus producing some fluid pathways, it will in general resist water movement through it. In the unsaturated zone, downward moving waters will tend to perch on the top of flow 9, and in the SRP aquifer the flow will probably act as a low-permeability mass requiring that waters move around it faster than through it. An evaluation of hydraulic conductivity by Anderson and others (1999) on nearby wells indicated the SRP aquifer is at approximately 480 ft depth in this area. Thus, flow 9 extends upward through the aquifer surface by about 50 ft. As it may affect the specific operation of the new percolation ponds as waters move down from their location, and also interact with periodic water infiltration along the course of the Big Lost River, perhaps the lateral extent of this thick flow will need to be better understood.

Only the deeper corehole USGS 128 has sampled flows underlying the above described flow sequence, and they are encountered under a 37-ft thick sedimentary interbed. Flows 12,

13 and 14 were differentiated by their physical core characteristics and to some extent by hand specimen petrographic variations. The paleoinclinations of these three lava flows are very similar with 53 to 55° values and show some steepening through the sequence of three flows. It is likely that these flows are of similar age, and by paleoinclination and depth correlation to corehole ICPP-123 that they represent all or in part the “I” flows (Anderson, 1991) which vent at AEC Butte (Lanphere and others, 1993). AEC Butte lava flows have been K-Ar and  $^{40}\text{Ar}/^{39}\text{Ar}$  dated at  $637 \pm 35$  ka (Champion and others, 2002). The “I” flow sequence is also broadly correlative in the subsurface of INTEC, TRA, and CFA and is an important unifying stratigraphic layer.

Flows 15 and 16 in the lowest portions of corehole USGS 128 are the last requiring some description. They have dissimilar paleoinclination values and petrographic character. The top samples of both flows are magnetically overprinted by their respective overlying flows, particularly the top three samples of flow 16. As they are unremarkable in these characteristics, and deep adjacent coring is unavailable, specific correlations to other wells cannot be made at the present time.

While subhorizontal correlation of basalt and sediment layers between these coreholes is the general rule, the deepest layers are found at progressively greater depths north to south. This is in all probability due to the progressive subsidence of the eastern SRP through time. A study of patterns of subsidence and accumulation for the southern INEEL area has recently been made (Champion and others, 2002). Though some irregularities may exist, the greatest subsidence rate is beneath the topographic axis of the eastern SRP, with lesser rates near the margins. The deeper layers correlated between coreholes and shown in figure 7 demonstrate this relative subsidence even though these basalt flows are only 600 to 700 ka in age. This is particularly true of well USGS 128 which is offset a mile farther southeast from the other three wells.

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Table 1. Stratigraphy, paleomagnetic inclination, and depth data for well ICPP-213.

Basalt flow	Inclination	Depth range
[sediment]		0 – 42 ft
1	(uncored)	42 – 57 ft
[sediment]		57 – 66 ft
2	$59.9^\circ \pm 1.3^\circ$	66 – 114 ft
3	(overprinted)	114 – 123 ft
[sediment]		123 – 138 ft
4	$72.8^\circ \pm 2.2^\circ$	138 – 181 ft
[sediment]		181 – 212 ft
5	$72.2^\circ \pm 0.9^\circ$	212 – 227 ft
[sediment]		227 – 234 ft
6	$62.6^\circ \pm 0.6^\circ$	234 – 251 ft
7	$59.9^\circ \pm 0.9^\circ$	251 – 298 ft
[sediment]		298 – 305 ft
8	$65.9^\circ \pm 0.8^\circ$	305 – 428 ft
9	$67.2^\circ \pm 1.1^\circ$	428 – 560 ft +

Table 2. Stratigraphy, paleomagnetic inclination, and depth data for well ICPP-214.

Basalt flow	Inclination	Depth Range
[sediment]		0 – 53 ft
1	$52.1^\circ \pm 1.6^\circ$	53 – 106 ft
2	$62.0^\circ \pm 1.6^\circ$	106 – 128 ft
[sediment]		128 – 146 ft
3	$77.4^\circ \pm 1.2^\circ$	146 – 168 ft
4	$59.0^\circ \pm 6.1^\circ$	168 – 182 ft
[sediment]		182 – 185 ft
5	$71.1^\circ \pm 1.4^\circ$	185 – 236 ft
[sediment]		236 – 242 ft
6	$64.0^\circ \pm 2.1^\circ$	242 – 253 ft
[sediment]		253 – 256 ft
7	$58.7^\circ \pm 1.1^\circ$	256 – 300 ft
[sediment]		300 – 306 ft
8	$65.1^\circ \pm 0.5^\circ$	306 – 503 ft+

Table 3. Stratigraphy, paleomagnetic inclination, and depth data for well ICPP-215.

Basalt flow	Inclination	Depth range
[sediment]		0 – 76 ft
1	$59.3^\circ \pm 1.5^\circ$	76 – 84 ft
[sediment]		84 – 85 ft
2	$62.6^\circ \pm 1.2^\circ$	85 – 122 ft
[sediment]		122 – 123 ft
3	$58.7^\circ \pm 1.3^\circ$	123 – 149 ft
[sediment]		149 – 159 ft
4	$53.7^\circ \pm 1.8^\circ$	159 – 188 ft
[sediment]		188 – 215 ft
5	$70.3^\circ \pm ??$	215 – 224 ft
6	$60.9^\circ \pm 1.2^\circ$	224 – 289 ft
[sediment]		289 – 291 ft
7	$62.3^\circ \pm 1.7^\circ$	291 – 332 ft
[sediment]		332 – 337 ft
8	$66.3^\circ \pm 0.8^\circ$	337 – 503 ft+

Table 4. Stratigraphy, paleomagnetic inclination, and depth data for well USGS 128.

Basalt flow	Inclination	Depth range
[sediment]		0 – 19 ft
1	$65.4^\circ - 2.1^\circ$	19 – 50 ft
2	$51.9^\circ \pm 2.6^\circ$	50 – 102 ft
3	$52.5^\circ \pm 1.2^\circ$	102 – 144 ft
[sediment]		144 – 148 ft
4	$50.5^\circ \pm 1.8^\circ$	148 – 184 ft
[sediment]		184 – 195 ft
5	$70.1^\circ \pm 2.1^\circ$	195 – 244 ft
[sediment]		244 – 248 ft
6	$64.1^\circ \pm 1.4^\circ$	248 – 283 ft
7	$60.1^\circ \pm 1.1^\circ$	283 – 346 ft
[sediment]		346 – 358 ft
8	$57.2^\circ \pm 1.3^\circ$	358 – 414 ft
[sediment]		414 – 423 ft
9	$67.4^\circ \pm 1.1^\circ$	423 – 545 ft
10	$68.5^\circ \pm 1.1^\circ$	545 – 573 ft
[lost core interval]		573 – 584 ft
11	$68.8^\circ \pm 1.1^\circ$	584 – 612 ft
[sediment]		612 – 649 ft
12	$55.4^\circ \pm 0.9^\circ$	649 – 666 ft
13	$54.5^\circ \pm 2.3^\circ$	666 – 694 ft
14	$53.3^\circ \pm 1.2^\circ$	694 – 714 ft
[sediment]		714 – 715 ft
15	$64.9^\circ \pm 1.6^\circ$	715 – 747 ft
16	$58.2^\circ \pm 1.8^\circ$	747 – 768 ft